BUILDING PENETRATION MEASUREMENTS FROM LOW-HEIGHT BASE STATIONS AT 912, 1920, AND 5990 MHz

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Building penetration measurements were taken simultaneously at three potential Personal Communications Services (PCS) frequencies: 912, 1920, and 5990 MHz. The continuous wave (CW) measurement system employed a fixed outdoor transmitter and a mobile indoor receiver. The goal was to quantify building penetration losses at these frequencies to determine the viability of indoor coverage using street microcells and base antenna heights below the roof level of surrounding buildings. Eleven different buildings representing typical residential and high-rise office building environments were used for the measurements. Vertically polarized transmit and receive antennas were used for all measurements. Statistical analyses of the data include mean building attenuation losses, standard deviations, cumulative probability distribution functions, and correlation coefficients. The analyses were used to characterize propagation effects and provide a comparison between three frequencies, two cell environments, and two transmission paths.

Key Words: *attenuation; building attenuation; building penetration; measurements; personal communications services; PCS; penetration characteristics; penetration loss; radio propagation*

1. INTRODUCTION

The mobile communications community has great interest in improving cellular system performance and developing new telecommunication services such as Personal Communications Services (PCS) and advanced cellular mobile systems. A significant system improvement would be the ability to use one mobile communication system in an uninterrupted manner both inside and outside buildings. If an outdoor microcell could provide coverage to indoor subscribers, it would be unnecessary to place base stations inside each building requiring coverage. This would eliminate the problems of handoff from the outdoor to the indoor transmitter, and reduce the costs of the system. Indoor picocell design would no longer be required. Locating the outdoor base station on an existing structure, such as a street or traffic light, would be particularly advantageous. To determine the viability of indoor coverage from an outdoor base station at

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traffic-light height, this paper presents the results of narrowband building penetration measurements (see Glossary of Terms) made in Boulder and Denver, Colorado, in the spring of 1993. The geometry of the test configurations suggests that the radio signals penetrated the buildings mainly via walls and windows, due to the low base antenna height (5 m).

The measurements were taken in residential and high-rise buildings (see Glossary of Terms) at 912, 1920, and 5990 MHz. Included in the measurements were all levels of the residences (including basements), and seven or eight nonconsecutive levels of the high rises, up to a maximum of the fifteenth level. The building penetration measurement system consisted of a three-frequency fixed transmitter positioned 25 to 200 m from the receiver. The transmitter was set at a height of 5 m to simulate the height of a street or traffic light. The receiver was held at a height of 1.9 m to simulate the height of a person using a phone. Path loss (see Glossary of Terms) data at 912, 1920, 5990 MHz were collected simultaneously as the receiver was moved inside the building under test. Data were recorded at 16-ms sampling intervals for a 50-s period while the receiver moved at an approximate speed of 0.75 m/s. At this speed/sampling interval we captured at least eight samples per wavelength, to ensure that we collected data during the deep fades which can be encountered every half-wavelength due to multipath. We recorded fades of up to 30 dB even at the highest frequency (see Figure 32).

The path loss data were analyzed to provide building attenuation statistics. The results of this data analysis provide a comparison between the three frequencies, two cell types, two transmission paths, and various floor heights of high-rise buildings.

2. MEASUREMENT SYSTEM

The measurement system configuration selected was advantageous because it allowed simultaneous measurement of received signal levels at multiple frequencies using a single communication channel. Using this method, we were ensured of obtaining signals at all frequencies which have been transmitted through exactly the same obstructions at exactly the same time. Thus, the analysis of building penetration loss as a function of frequency was expected to be more reliable than could be achieved using other testing configurations.

2.1 Equipment Description

The system consisted of a fixed transmitter and a mobile receiver. The transmitter was located on the street near the building under test, emulating a microcell base station. The receiver was carried manually throughout the building under test. The maximum distance from transmitter to receiver was restricted to 300 m in order to keep the received signal strength within the dynamic range of the low-power test equipment.

2.1.1 Transmitter

A vertically polarized, omnidirectional antenna was used to transmit three frequencies simultaneously. The antenna was positioned at a height of 5 m by means of a telescoping mast. This height was selected to emulate typical street microcell base stations mounted on existing structures such as street or traffic lights. The antenna had an omnidirectional azimuthal pattern, and a 60-, 35-, and 20-degree-elevation beamwidth for 912, 1920, and 5990 MHz, respectively.

A van was used to house and transport the transmitter equipment (Figure 1). Although the transmitter could be moved, it remained in a fixed location for the duration of the line-of-sight (LOS) and non-line-of-sight (NLOS) experiments (see Glossary of Terms) at each building. In order to ensure valid comparisons among the data collected, all data for each transmission path was collected in a single day while the transmitter remained in a fixed location. The transmitter was powered by a diesel generator which was towed behind the van. Three unmodulated waves at 912, 1920 and 5990 MHz were radiated simultaneously by one antenna. Two transmission paths were measured for each building: one for LOS and one for NLOS data collection. For

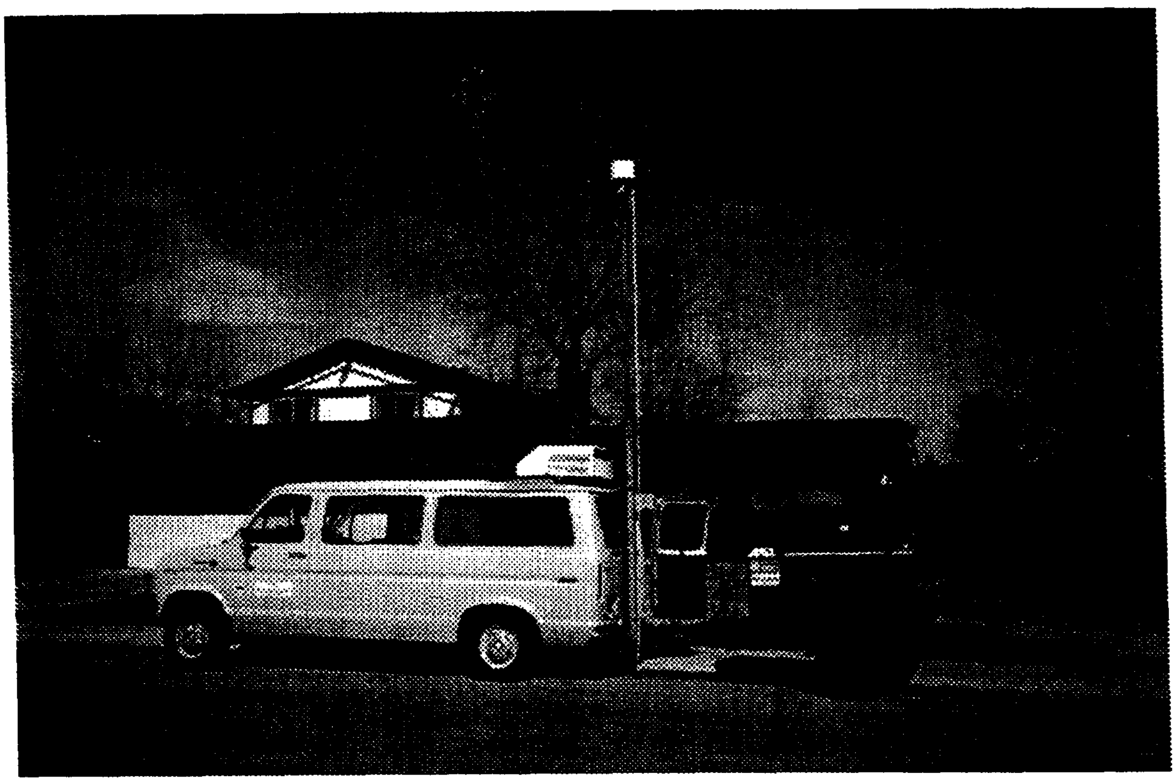

Figure 1. Photograph of van used to transport transmitter equipment.

the high-rise building measurements, the transmitting antenna was tilted to an angle of 24 degrees from horizontal. This allowed the main beam of the antenna to illuminate more floors of the building, and reduced the impact of the narrow-beamwidth antenna elevation patterns.

The three transmitted signals were generated by three frequency synthesizers. The signals were amplified and filtered separately to avoid intermodulation distortions, and combined by a quadruplexer with the unused input loaded. The combined signal was fed through a low-loss cable to the wideband, omnidirectional vertically polarized antenna. Figure 2 shows the block diagram of the transmitting equipment.

The measured input to the antenna was 15 dBm. The antenna gain was 0, 2.6, and 3.6 dBi at 912, 1920, and 5990 MHz, respectively. The effective isotropic radiated power (EIRP) from the transmitter is the sum of the input and the gain, or 15, 17.6, and 18.6 dBm at 912, 1920, and 5990 MHz, respectively.

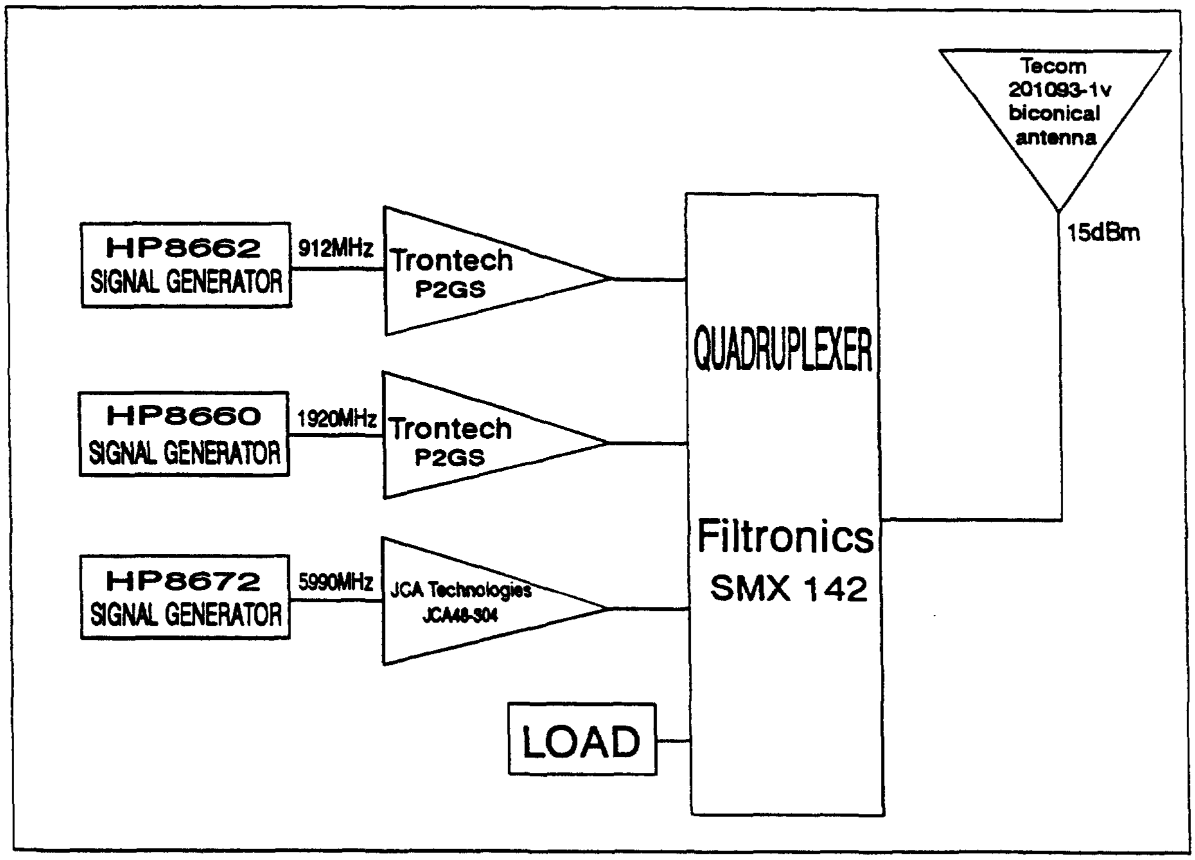

Figure 2. Block diagram of transmitter equipment.

2.1.2 Receiver

The receiver equipment, shown in Figure 3, consisted of an omnidirectional, vertically polarized antenna, identical to the transmitting antenna. The receiving antenna was manually carried through the buildings, supported by a special harness. This kept the antenna vertical, kept the antenna height constant (1.9 m), and avoided head shadowing. The received signal was divided by a quadruplexer with the unused output terminated. The active outputs of the quadruplexer were individually filtered and amplified. To decrease the noise figure of the system, the quadruplexer, filters, and low-noise amplifiers were secured to the antenna and fed through short, low-loss cables. To allow for mobility of the antenna, the signal was passed through 30 m of low-loss coaxial cables before entering three spectrum analyzers. The 5990-MHz channel included a second low-noise amplifier inserted at the input to the spectrum analyzer to

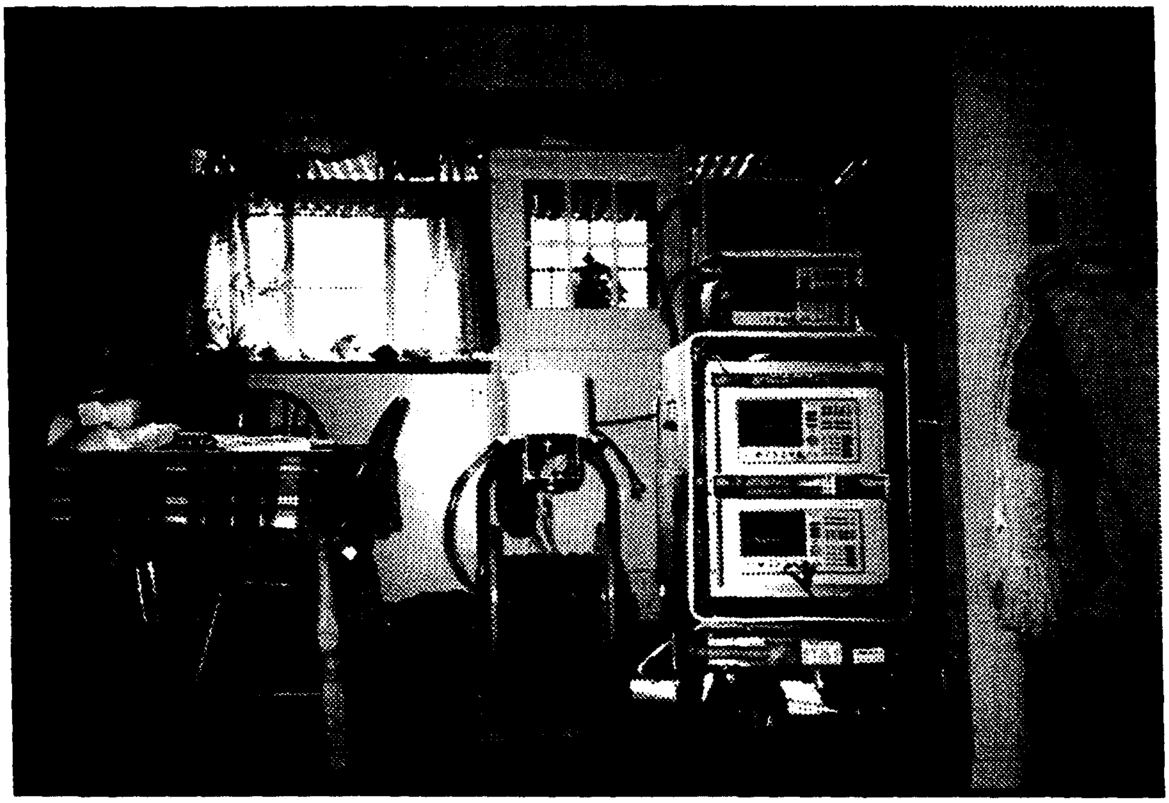

Figure 3. Photograph of receiver system.

make up for the relatively higher loss of the long coaxial cable at the higher frequency. The spectrum analyzers were controlled and the data collected automatically over a general purpose interface bus (GPIB) by a personal computer (PC). A functional block diagram of the receiver equipment is shown in Figure 4.

The measured gain of the receiver amplifiers was 26, 26, and 37 dB at 912, 1920, and 5990 MHz, respectively. The antenna gain was 0, 2.6, and 3.6 dBi at 912, 1920, and 5990 MHz, respectively. The calculated gain of the receiver relative to isotropic gain is the sum of the antenna gain and the receiver amplifier gain, or 26, 28.6, and 40.6 dB at 912, 1920, and 5990 MHz, respectively..

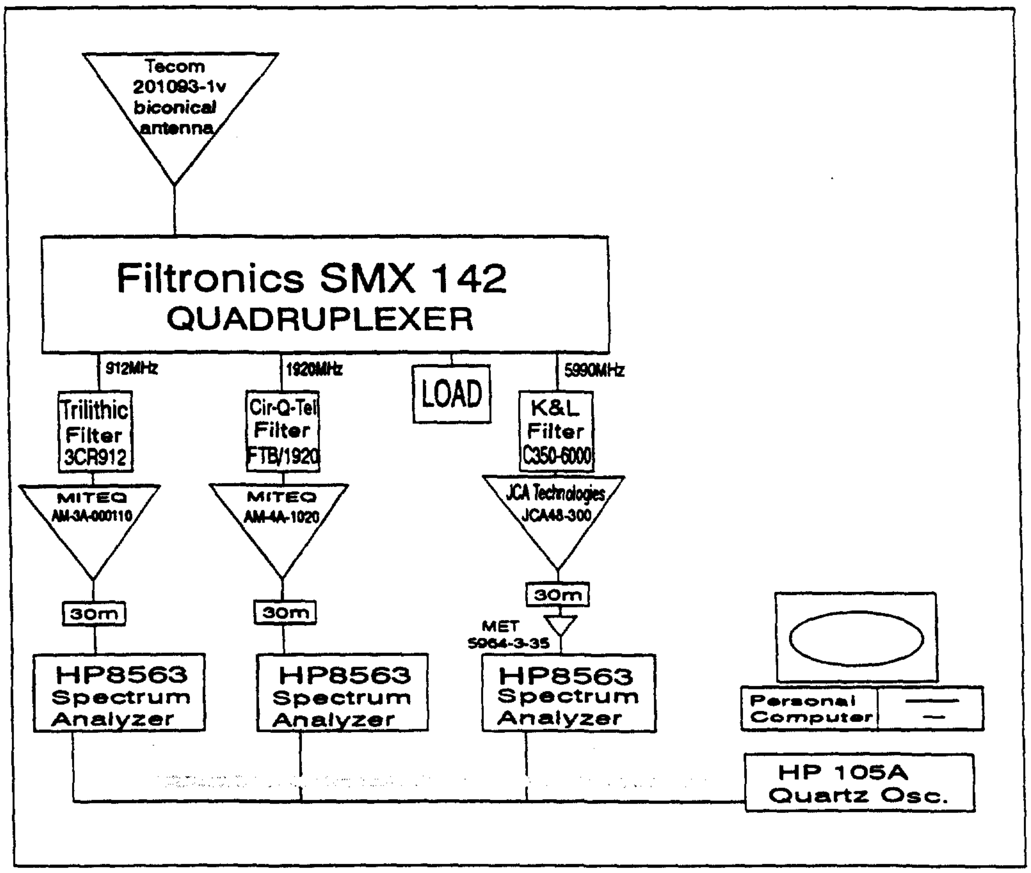

Figure 4. Block diagram of receiver equipment.

2.2 Calibration and Measurement Procedure

The transmitter was calibrated every morning (after allowing adequate time for the system to reach operating temperature) with a spectrum analyzer to ensure that all frequencies produced 15 dBm at the input to the antenna. The receiver was calibrated with a noise diode every morning and every afternoon. All spectrum analyzers were self-calibrated before measurements were taken in each room.

Although precise distance measurements were not required, a precision electronic distance meter (EDM) was used as the easiest means of gathering distance information. All distance measurements reported here are approximations within 10 m.

Reference measurements (see Glossary of Terms) were made at ground level outside each building, one for each transmission path. To avoid the possibility of measuring a deep fade caused by multipath as the reference, a zig-zag pattern with a radius greater than the longest transmitted wavelength was traversed along outside walls of each building. A minimum sample of 100 wavelengths was collected for each reference.

Within the buildings, the measurements were made by moving the receiving antenna in a zig-zag pattern through the area measured. This pattern was used to ensure that the entire area was covered, not just the perimeter. In the residential measurements, a zig-zag pattern was traversed across the full area of each room. Five representative rooms were measured to acquire an average for each residential building. For the high-rise building measurements, a zig-zag pattern was traversed across each of the four corners (except in instances where we were denied access to the area) on representative floors, covering an area of approximately 40 m^2 per corner.

In each room measured, a zig-zag pattern with each leg greater than the maximum transmitted wavelength (0.66 m) was traversed. To avoid aliasing, we collected four samples per the shortest wavelength (0.05 m), or 80 samples per meter. A sampling rate of 60 Hz (601 samples in a 10-s sweep) was set by the spectrum analyzer, and the speed of the receiver was 0.75 m/s. Taking samples of at least 100 wavelengths per room gave us a minimum data collection time of 41 s. By collecting 5 sweeps of the spectrum analyzer, we collected a minimum of 3000 samples or 750 wavelengths per room. Thus we could observe the fast and slow fading effects, and deep fades (30 dB) at the shortest wavelength.

2.3 Data Format

The data were stored in ASCII format on the hard disk of a PC, and downloaded to floppy disk daily. Since five 10-s sweeps were taken in each room or corner, five files were generated. Each file contained data from all three frequencies. The equipment was then moved to the next room or corner, and the process was repeated. Because the signals were received by spectrum analyzers, real-time data were viewed as they were collected. This allowed the measurements to be checked immediately and retaken if erroneous.

3. MEASUREMENT LOCATIONS

3.1 Residential Building Information

We took measurements at seven private residences in and around Boulder, Colorado. Data were taken on the main floor, as well as in the basements and on second floors, when present. Figures 5 through 11 show the LOS and NLOS paths, and neighborhood layouts for each residence. In these figures, "TX" refers to the transmitter locations, and "RX" refers to the receiver location. Appendix A contains path loss and building layout information for all residential measurements.

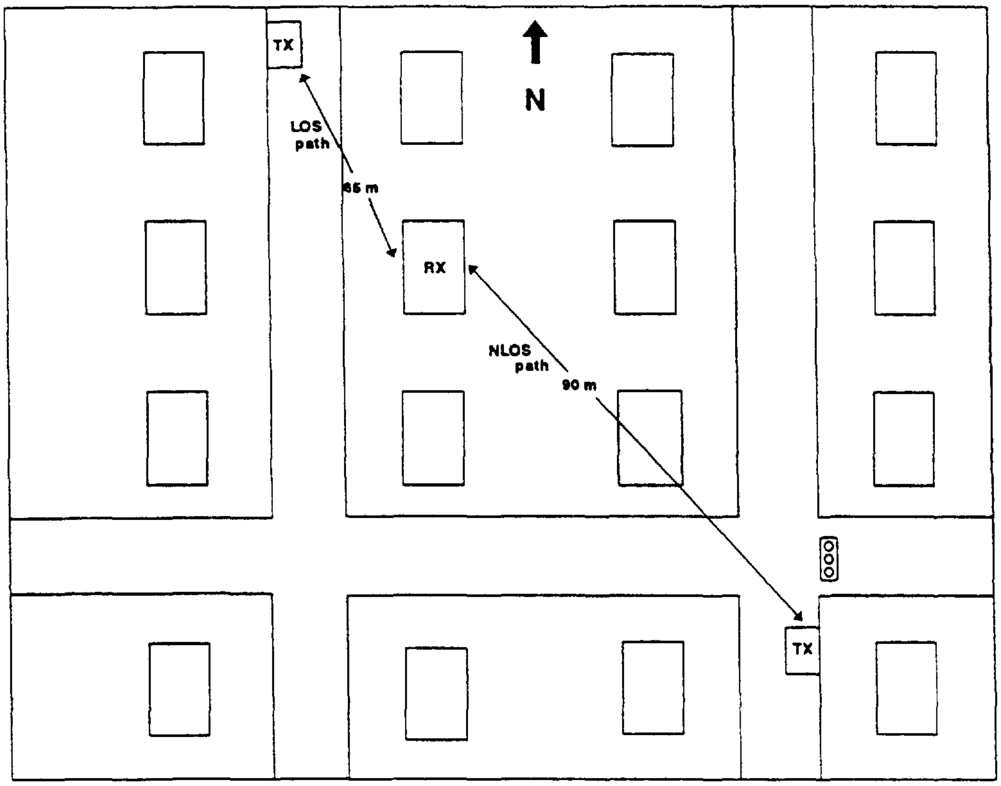

Figure 5. Diagram of residence-1 neighborhood (not to scale).

Residence 1 was a single-story brick, wire mesh, and plaster house. The closest street contained fewer then ten parked cars, and fewer than ten cars passed by per hour. The surrounding streets contained single-story houses, with approximately 800 m^2 of land each. In front of the house were two 15-m pine trees. The basement was completely underground with small window wells. For the LOS measurements, the transmitter was located 65 m northwest of the building. For the NLOS measurements, the transmitter was located 90 m southeast of the building.

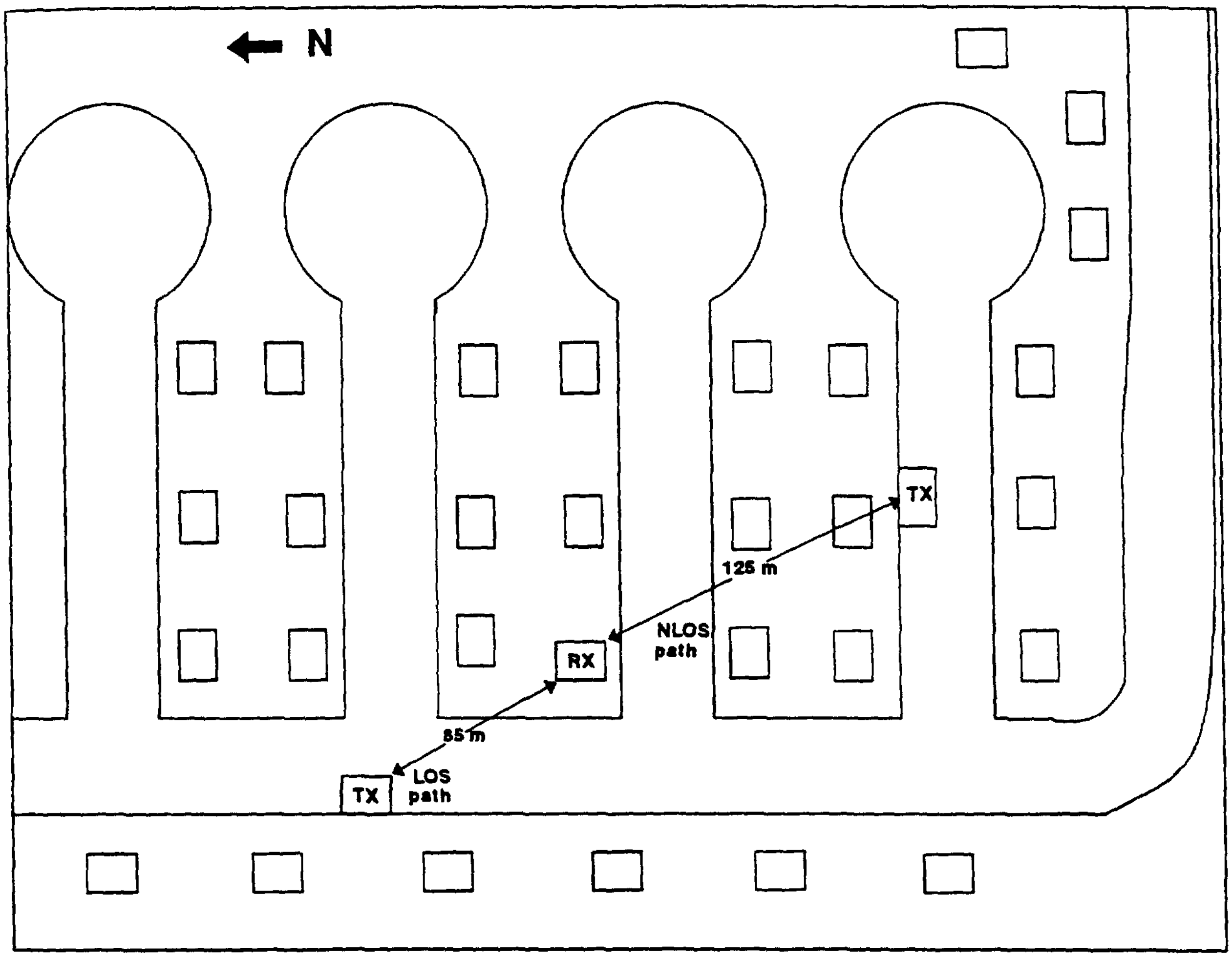

Figure 6. Diagram of residence-2 neighborhood (not to scale).

Residence 2 was a tri-level, brick veneer and wood building located on a street with fewer than ten cars passing per hour and no parked cars. The surrounding streets contained one- and two-story houses, with approximately 1200 m^2 of land per house. There were two 15-m tall pine trees located on the northwest side of the house. The basement was half underground and had large, above ground windows. For the LOS measurements, the transmitter was located 85 m northwest of the building. For the NLOS measurements, the transmitter was located 125 m southeast of the building.

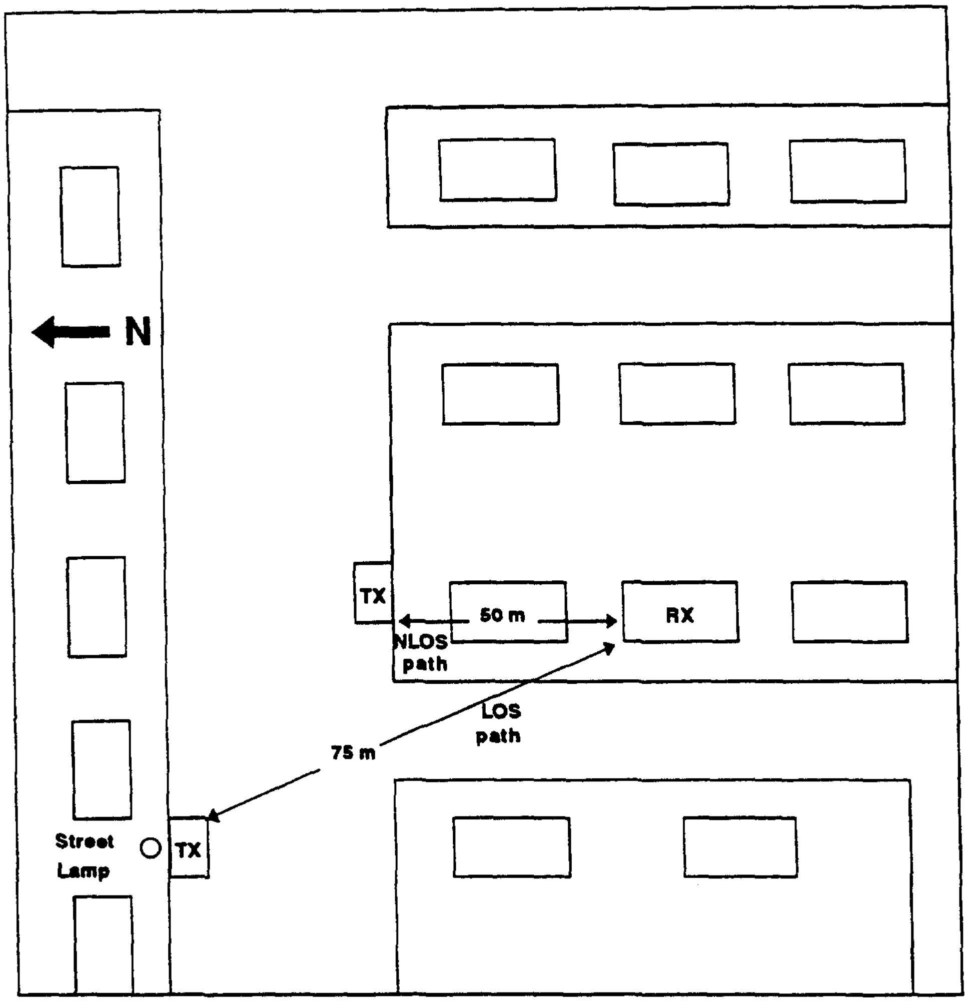

Figure 7. Diagram of residence-3 neighborhood (not to scale).

Residence 3 was a single-story, brick veneer building located on a street with fewer than ten passing cars per hour and no parked cars. The surrounding streets contained one- and two-story houses, with approximately 1200 m^2 of land per house. There was one 8-m tall bare tree and some 1-m tall evergreen shrubs around the house. The basement was completely underground and had small window wells. For the LOS measurements, the transmitter was located 75 m northwest of the building. For the NLOS measurements, the transmitter was located 50 m north of the building.

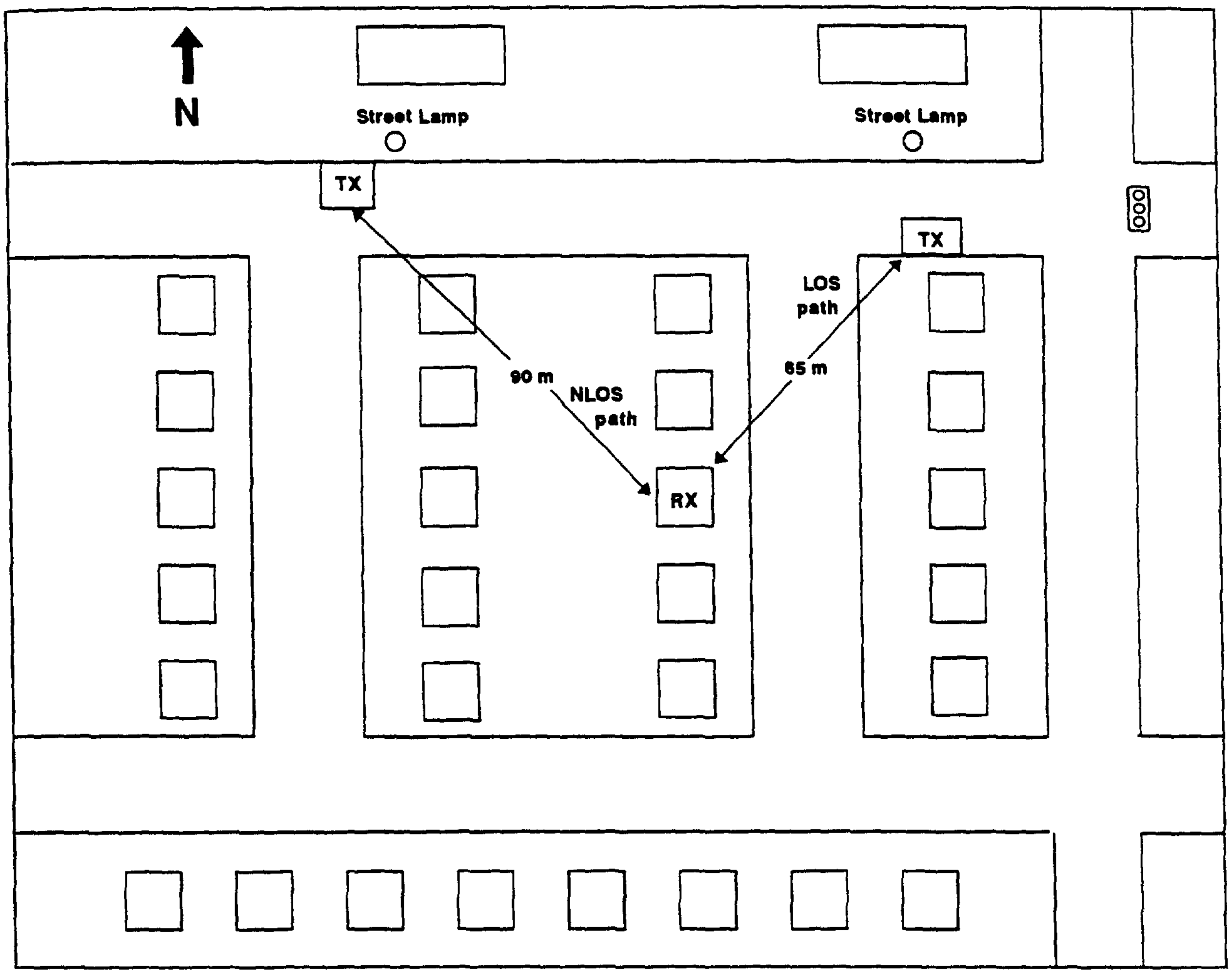

Figure 8. Diagram of residence-4 neighborhood (not to scale).

Residence 4 was a tri-level, brick building located on a street with fewer than 20 cars passing per hour. There were more than ten cars parked along the street near the house. The streets contained one- and two-story houses, with approximately 800 m^2 of land per house. The basement was half underground with large windows. For the LOS measurements, the transmitter was located 65 m northeast of the building. For the NLOS measurements, the transmitter was located 90 m northwest of the building.

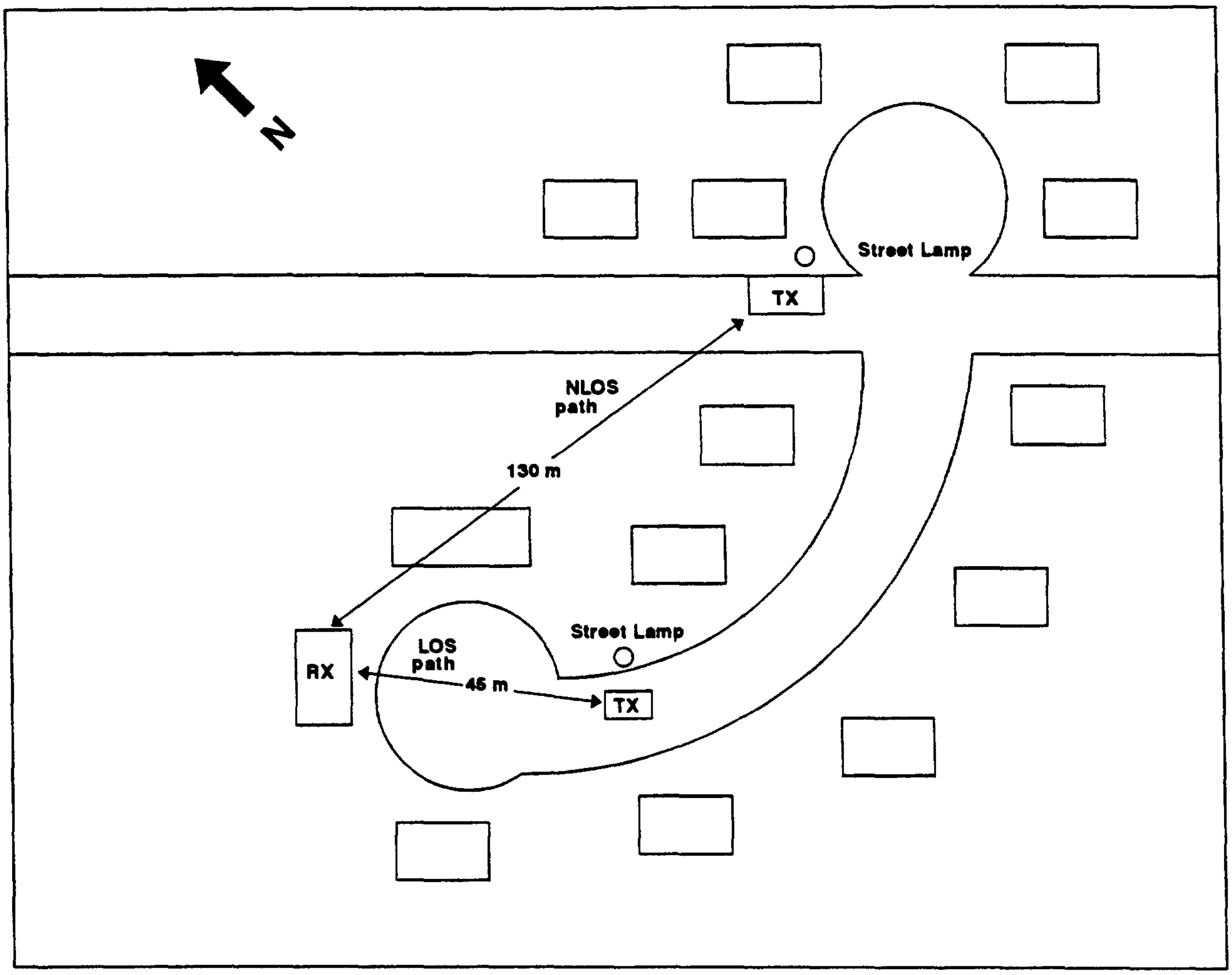

Figure 9. Diagram of residence-5 neighborhood (not to scale).

Residence 5 was a large, two-story, wood and brick veneer building with Thermoply® reflective insulation. It was located on a cul-de-sac with fewer than five cars passing per hour, and no cars parked on the street. The street contained large two-story houses, approximately 2000 m^2 of land per house, and no vegetation. The basement was completely underground and had large window wells. For the LOS measurements, the transmitter was located 45 m southeast of the building. For the NLOS measurements, the transmitter was located 130 m east of the building.

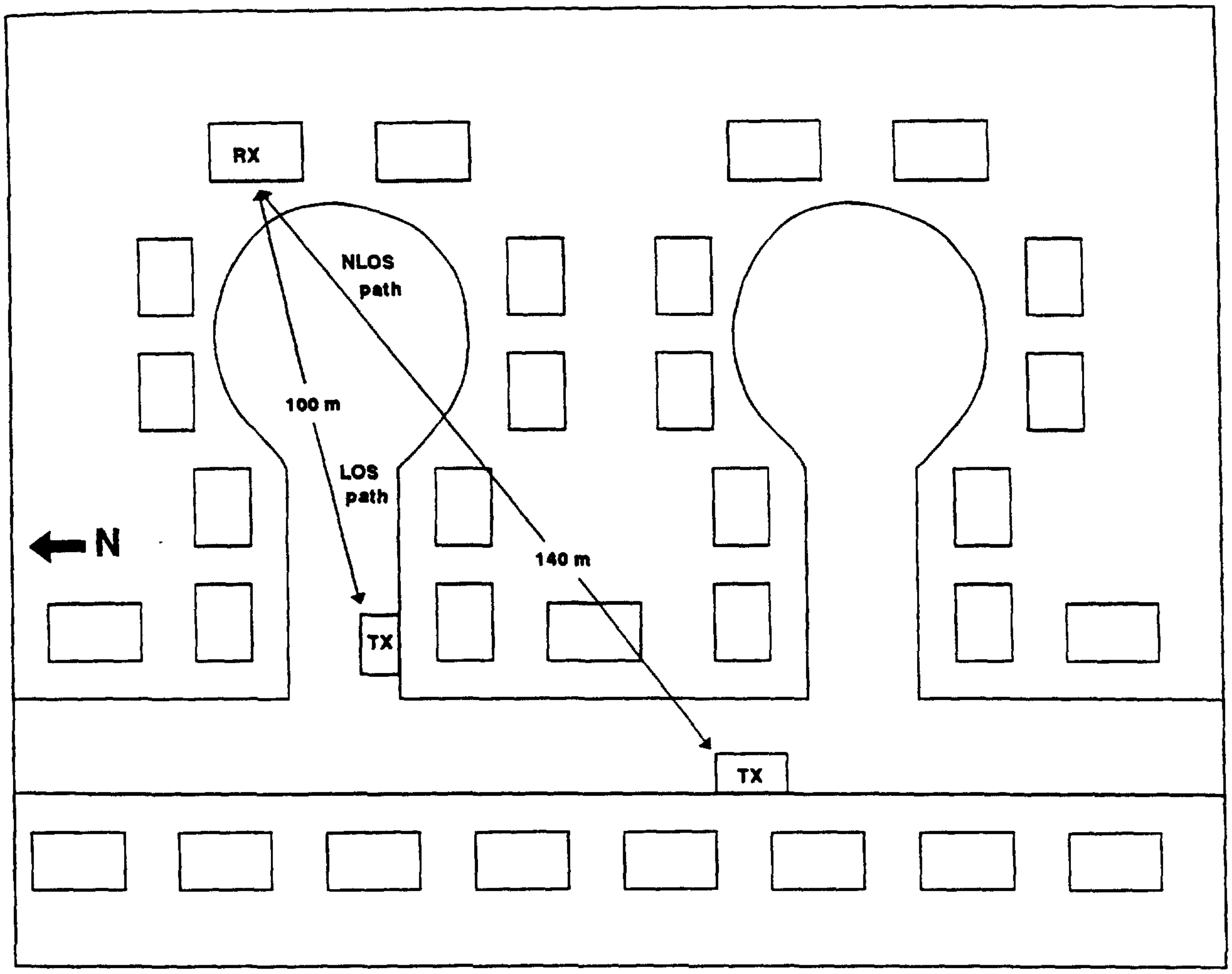

Figure 10. Diagram of residence-6 neighborhood (not to scale).

Residence 6 was a two-story, aluminum and brick veneer building located on a street with fewer than five cars passing per hour and fewer than five cars parked on the street. The street contained one- and two-story houses, with approximately 1000 m^2 of land per house. The basement was completely underground and had small window wells. For the LOS measurements, the transmitter was located 100 m southwest of the building. For the NLOS measurements, the transmitter was located 140 m southwest of the building.

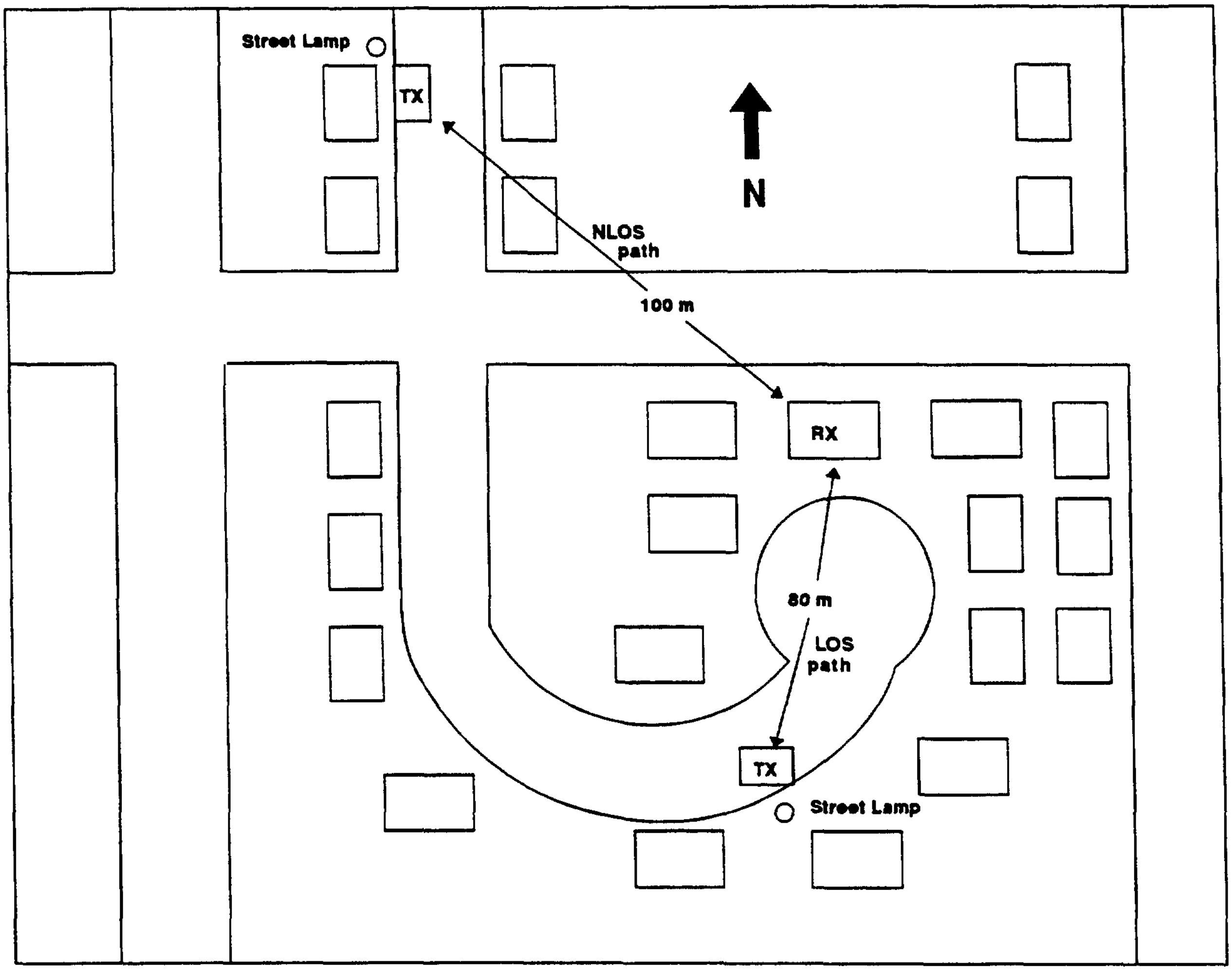

Figure 11. Diagram of residence-7 neighborhood (not to scale).

Residence 7 was a two-story, wood and brick veneer building located on a street with fewer than ten cars passing per hour. The surrounding streets contained one- and two-story houses, with approximately 800 m^2 of land per house. The basement was completely underground and had large window wells. For the LOS measurements, the transmitter was located 80 m south of the building. For the NLOS measurements, the transmitter was located 100 m northwest of the building.

3.2 High-rise Building Information

We took measurements in four high-rise buildings in downtown Denver, Colorado (Figures 13 through 16). This area consisted of closely spaced buildings with heights typically ranging from 3 to 30 stories. A diagram of the environment, with the total number of floors listed for each building, is shown in Figure 12. Due to logistical considerations, the transmitter was not parked under street lamps or traffic lights, but was parked to ensure appropriate transmission paths. For all high-rise buildings measured, the surrounding streets contained more than 20 parked cars, and more than 200 vehicles and 50 pedestrians passed per hour. The interiors of the high-rise buildings had an open-face layout with soft, low, cubicle-wall partitions. Appendix B contains the path loss data for each high-rise building measured.

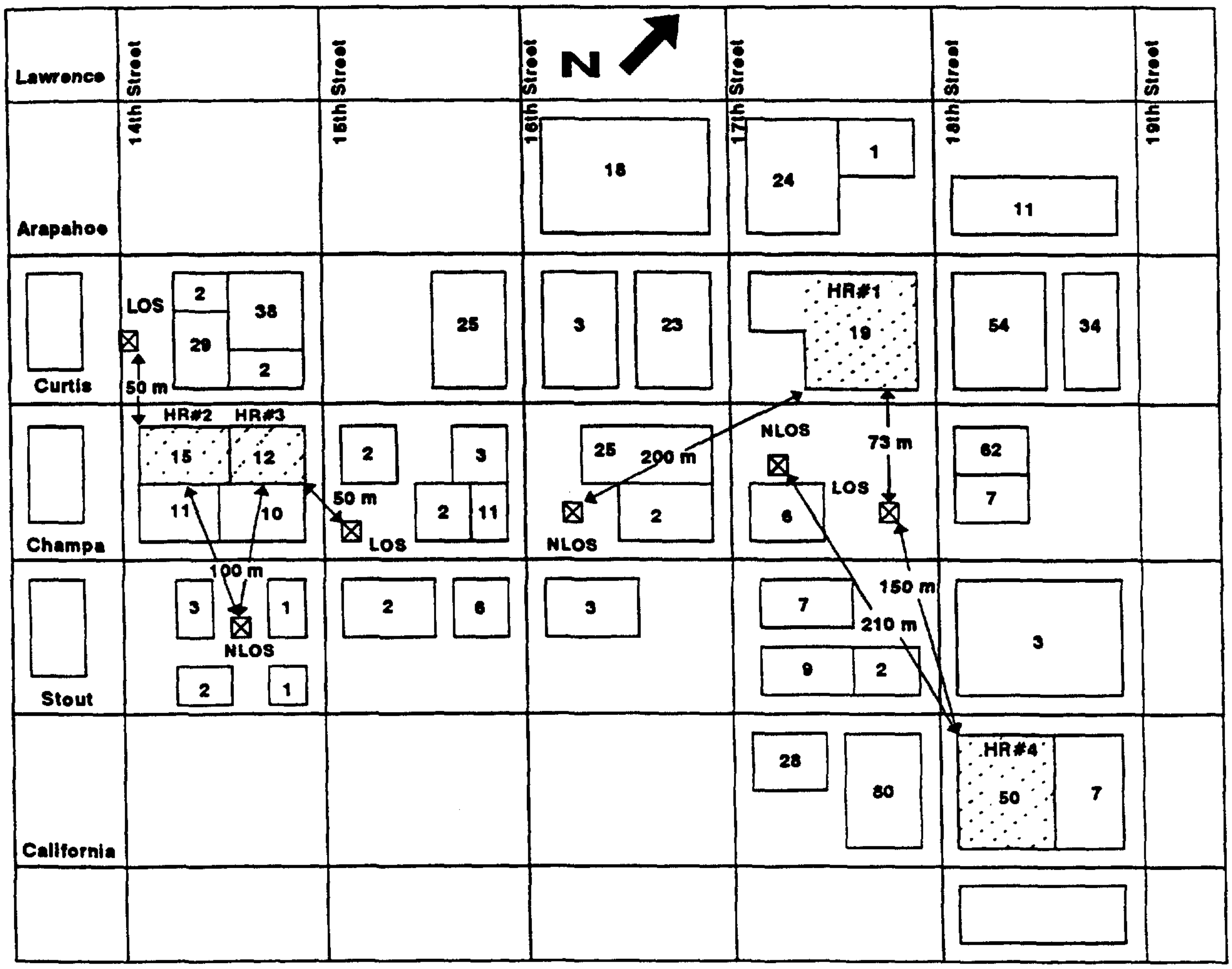

Figure 12. Area studied in Denver, Colorado. (Numbers indicate the number of stories for each building shown; not to scale.)

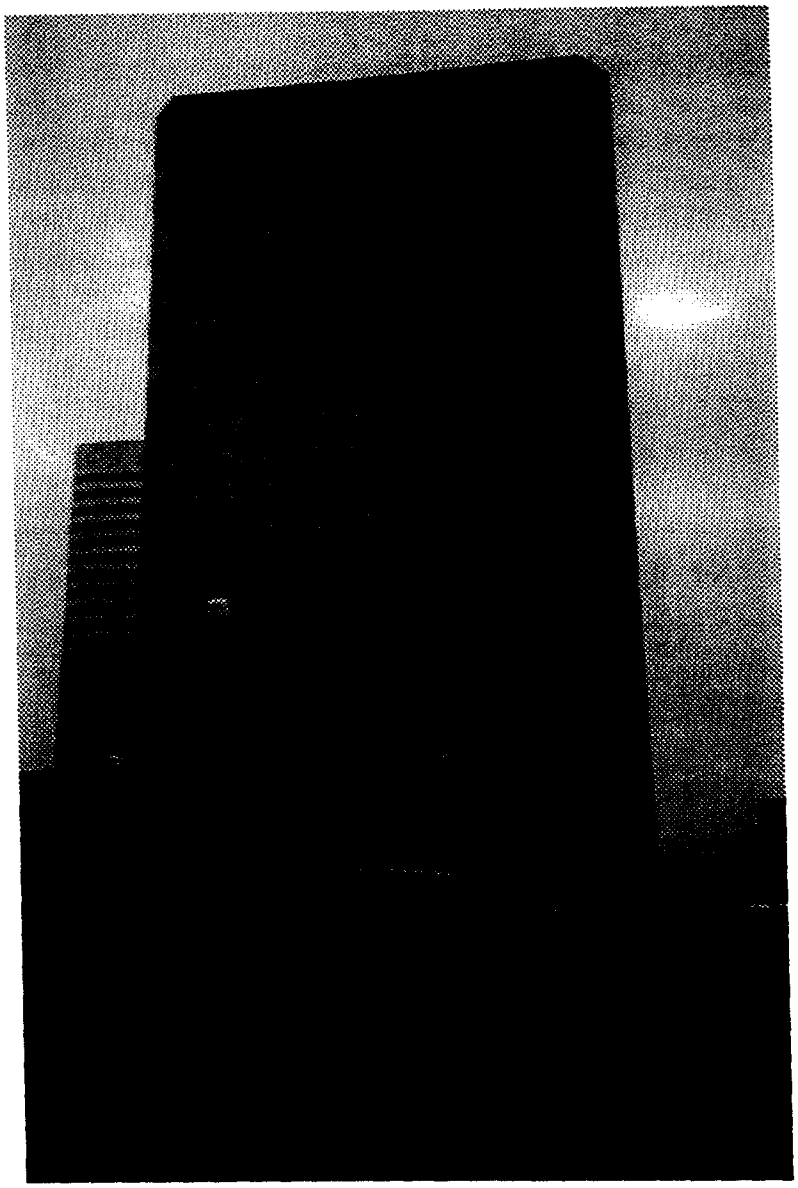

Figure 13. Photograph of high rise 1.

High rise 1 was a new 19-story building constructed of concrete, with long walls of glass on each floor. There was a fire wall separating the southeast side of the building from the northwest side. There were five leafless deciduous trees planted south of the building. The first floor was approximately 6 m above ground level. There were four levels under ground level, including three areas for automobile parking. For the LOS measurements, the transmitter was located 70 m southeast of the building. For the NLOS measurements, the transmitter was located 200 m southwest of the building.

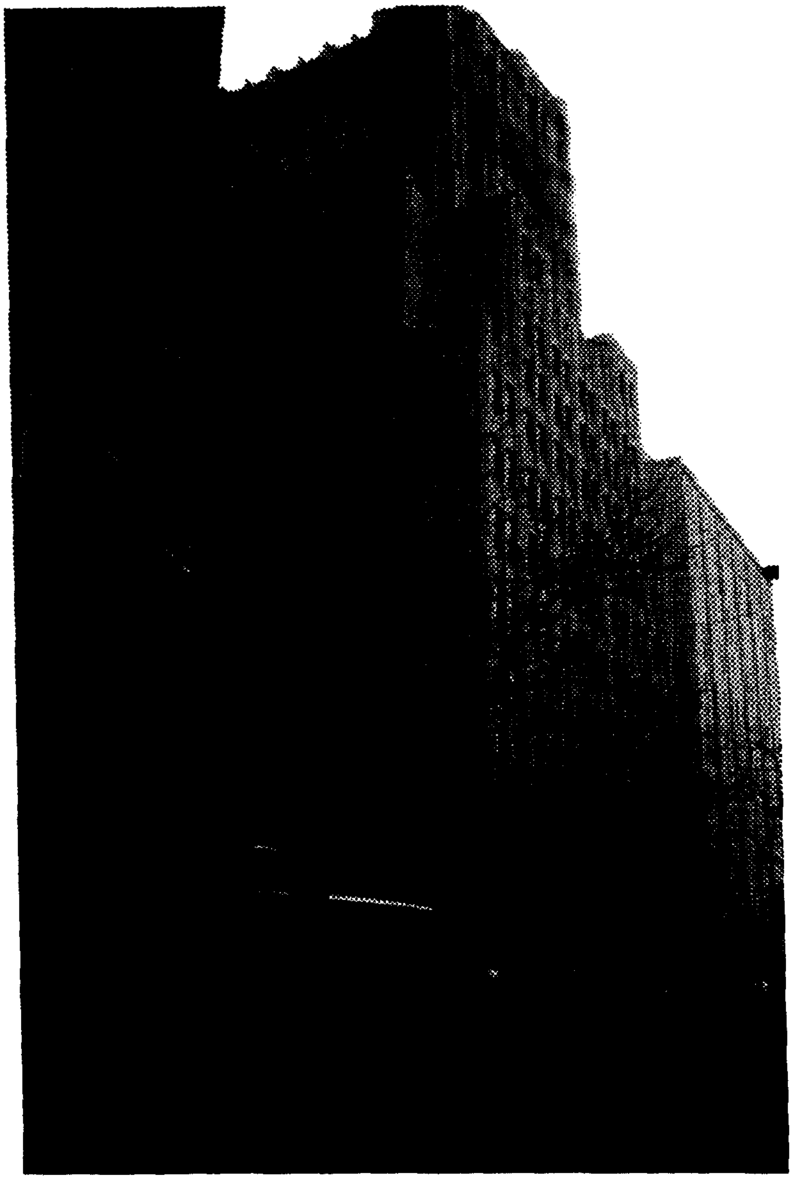

Figure 14. Photograph of high rise 2.

High rise 2 was a 65-year-old, 15-story, stone building with many windows evenly spaced throughout the building. There were two leafless deciduous trees to the northwest of the building. For the LOS measurements, the transmitter was located 50 m northwest of the building. Because of the layout of the city, only the west and south corners of the building were line-of-sight to the transmitter and were measured. For the NLOS measurements, the transmitter was located 100 m southeast of the building.

Figure 15. Photograph of high rise 3.

High rise 3 was a 12-floor, stone building with a column of windows running down the center of two sides of the building. It comprised one quarter of the block. There was no surrounding foliage. For the LOS measurements, the transmitter was located 50 m east of the building. Due to the layout of this block, only the east and north corners were line-of-sight to the transmitter and were measured. For the NLOS measurements, the transmitter was located 100 m southeast of the building.

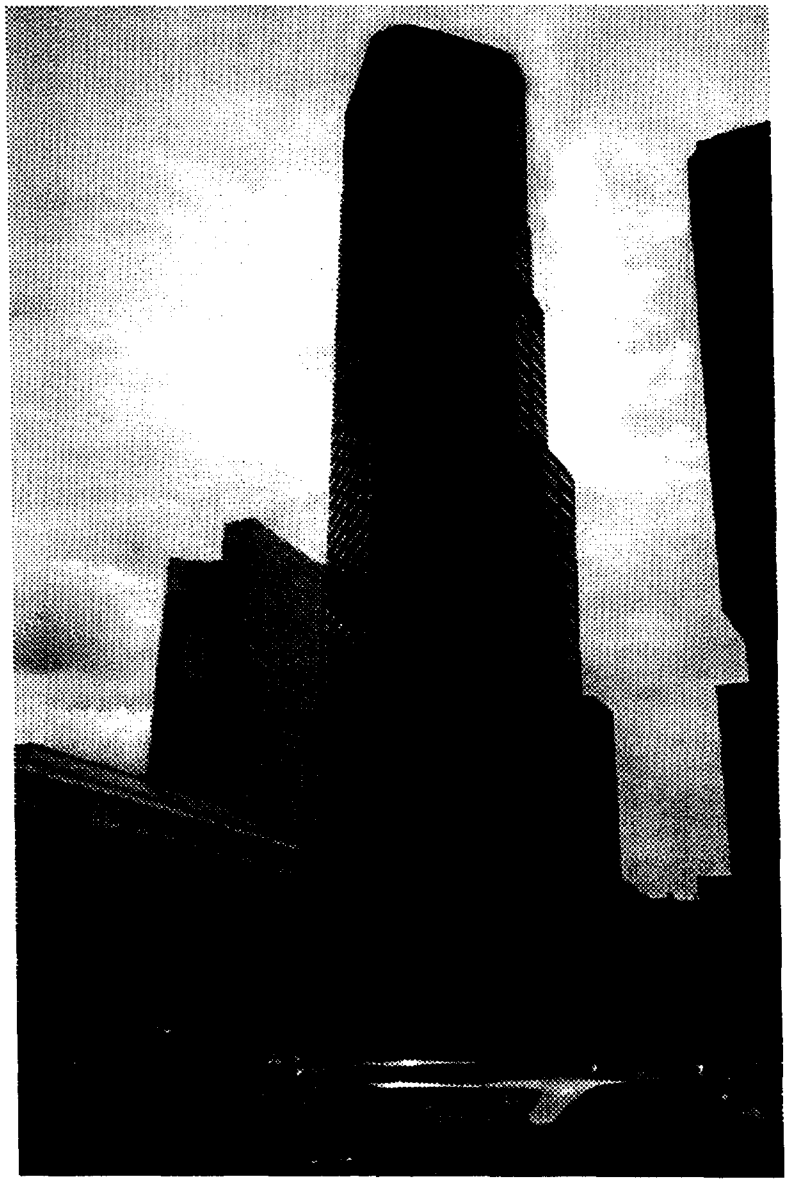

Figure 16. Photograph of high rise 4.

High rise 4 was a new 50-story building, which varied in shape as the floor levels increased. It was constructed of concrete and had many windows evenly distributed throughout the building. There was no surrounding foliage. For the LOS measurements, the transmitter was located 150 m northwest of the building. For the NLOS measurements, the transmitter was located 210 m northwest of the building.

4. DATA ANALYSIS

For point-to-multipoint communication environments, narrowband propagation characteristics can be described as a combination of three components: path loss, slow fading, and fast fading. This is illustrated in Figure 17, where received signal strength is shown as a function of distance. Knowledge of these components helps determine the required distance between cell sites, handoff speed, and signal-to-noise ratio.

Before initiating any path loss calculations, we corrected all raw data to subtract the gain introduced by the system hardware. The transmitter gain was 15, 17.2, and 18.6 dBi at 912, 1920, and 5990 MHz, respectively. The receiver gain was 26, 28.6, and 40.6 dB at 912, 1920, and 5990 MHz, respectively. The correction factor was 41, 45.8, and 59.2 dB at 912, 1920, and 5990 MHz, respectively.

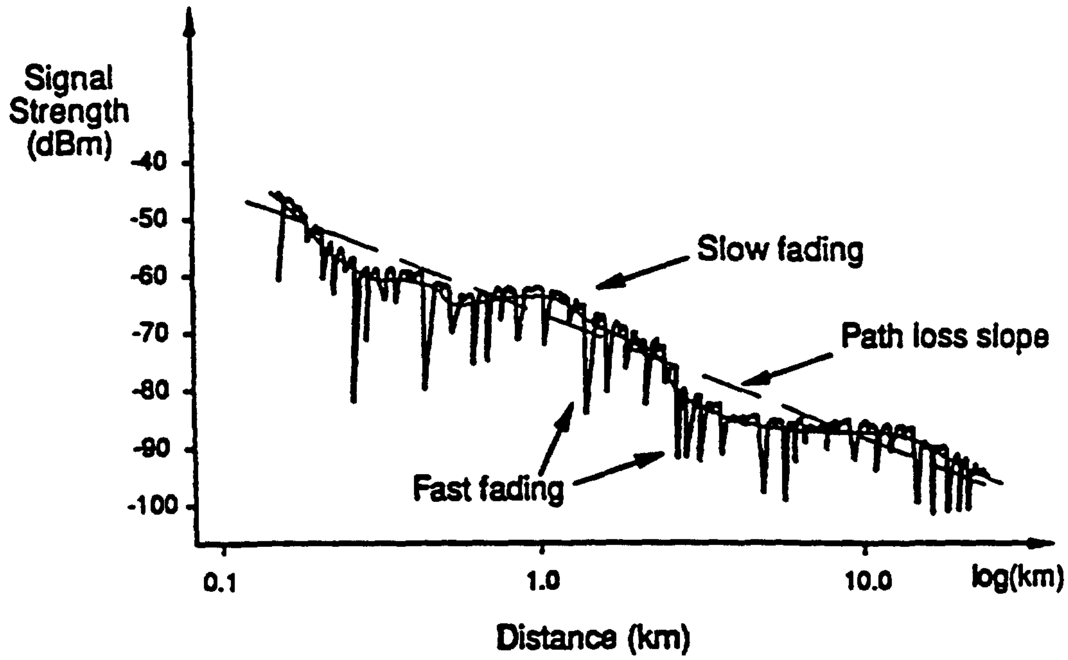

Figure 17. Characteristics of narrowband fading [2]. This graph is intended for use in this report to illustrated fading characteristics. Some data points may have been omitted for clarity.

4.1 Path Loss Calculations

As the distance separating a transmitter and receiver increases, the received signal strength tends to decrease due to wave spreading. This type of attenuation is known as path loss (see Glossary of Terms). Knowledge of the amount of path loss expected is critical in determining cell sizes for optimum performance of PCS systems.

The theoretical path loss, L_T, in decibels can be expressed mathematically as

$$L_T = L + X \log(d), \tag{1}$$

where L is a loss constant which includes antenna gain,
X is the attenuation factor (dB/decade), and
d is the distance between transmitter and receiver.

In free space, the attenuation factor is 20 dB/decade. We expect this value to be larger in building penetration measurements.

The experimental median (see Glossary of Terms) path loss, L_M, in decibels between the transmitter and receiver can be calculated from the measured data using the formula

$$L_M = P_{RX} - P_{RX\_ideal}, \tag{2}$$

where P_{RX} is the median measured power at the receiver (dBm), and
P_{RX_ideal} is the ideal received power (dBm).

Median measured path loss for all residential and high-rise buildings is shown in Appendix A and Appendix B, respectively. Path loss versus distance plots are shown in Figures 18 through 20. These plots include all buildings and transmission paths measured. Each data point represents the median path loss per building and the average horizontal distance between transmitter and receiver.

Appendix C shows the path loss distribution for a selection of rooms in the residential buildings, and floors of the high-rise buildings. These histograms show uni-modal and bi-modal distributions.

4.1.1 Breakpoint

There is a phenomenon referred to as the path loss breakpoint [3,4,5]. It consists of a change in path loss slope at some radial distance from the transmitter. It is caused by the reflection of the transmitted signal by the ground. This multipath signal interferes with the direct path signal and usually occurs only in areas with clear LOS and ground reflection paths. Theoretically, the path loss should decrease 20 dB/decade close to the transmitter, and decrease 40 dB/decade after

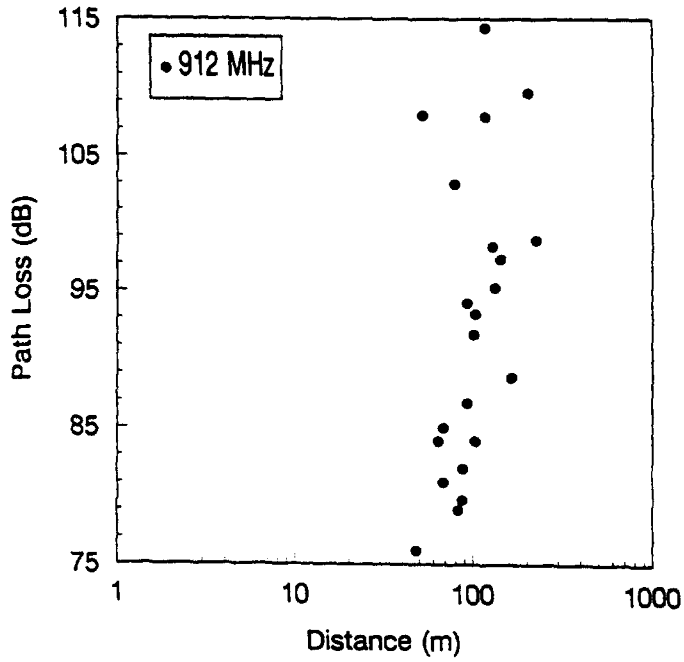

Figure 18. Path loss versus distance at 912 MHz.

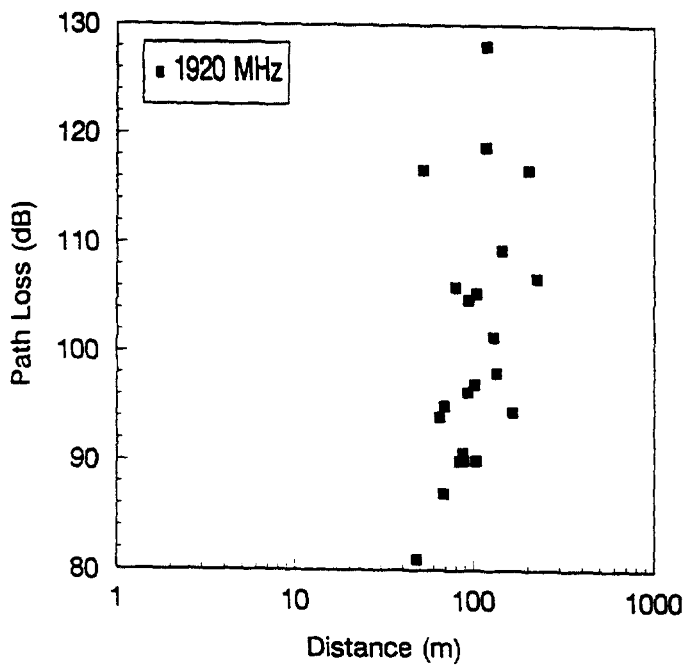

Figure 19. Path loss versus distance at 1920 MHz.

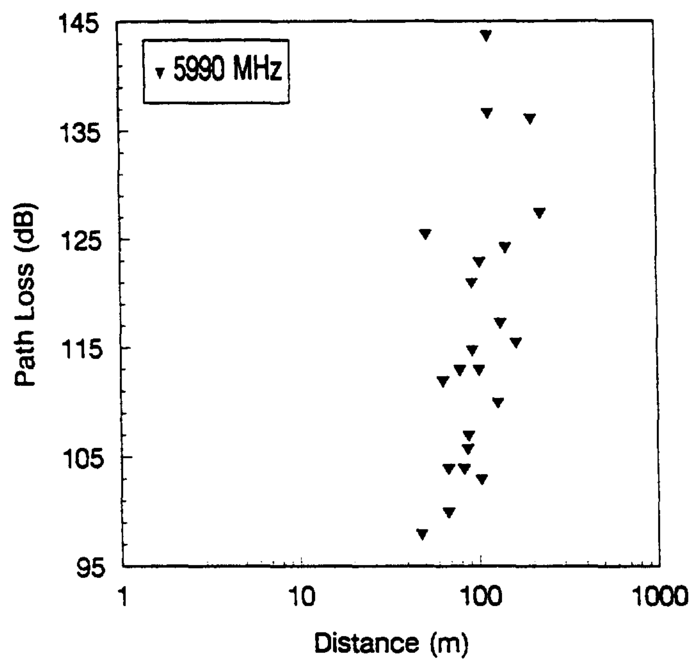

Figure 20. Path loss versus distance at 5990 MHz.

the path loss breakpoint occurs. (Note: this phenomenon helps to increase spectrum efficiency by allowing for increased frequency reuse at distances larger than the breakpoint.) The breakpoint radius from the transmitter, R_b, can be calculated using the formula

$$R_b = \frac{2h_t h_r}{\lambda}, \tag{3}$$

where h_t is the height of the transmitting antenna,
h_r is the height of the receiving antenna, and
λ is the wavelength, all in the same units [6].

The expected breakpoint radii for our data are given in Table 1. Since our measurements were taken for microcells, we do not have a wide range of distance data. This makes it more difficult to determine a breakpoint. Also, the more obstacles and terrain changes between the transmitter and receiver, the less likely it becomes that a breakpoint will be seen [6]. Since half of our data was non-line-of-sight, half of the data points are likely to show no breakpoint. For the 5990-MHz data, we do not expect to see a breakpoint because all our measurements were taken at less than the calculated breakpoint radius of 400 m. For the data presented in this paper, no breakpoints were determined.

Table 1. Expected Breakpoint Radii

Frequency (MHz)	R_b (m)
912	60
1920	130
5990	400

4.1.2 Difference in Received Signal Strength

Received signal strength is an important parameter in telecommunications because it indicates the amount of transmitter power necessary to obtain coverage in an area. Received signal strength is calculated using the free space formula

$$P_r = P_t G_r G_t \frac{\lambda^2}{(4\pi r)^2}, \tag{4}$$

where P_r is the received power,
P_t is the transmitted power,
G_r is the gain of the receiving antenna,
G_t is the gain of the receiving antenna, and
r is the distance between transmitter and receiver.

The antenna gains are calculated using the formula

$$G = A_e \frac{4\pi}{\lambda^2}, \tag{5}$$

where A_e is the effective aperture of the antenna and
G is the antenna gain.

Since all variables except the frequency are held constant in our application, the theoretical change in received signal strength (power) due to the change in frequency transmitted is determined by

$$\Delta P_r = 20 \log(f_2/f_1). \tag{6}$$

The expected and measured differences between the frequencies are given in Table 2. The measured differences vary from the calculated values quite significantly. This variance is well-established by our measurements, being observed in both urban and suburban environments. These findings concur with other research findings, where differences in received signal strength of up to 4 dB (1922/880 MHz) greater than theory were found [5,7,8,9].

Table 2. Received Signal Strength Differences Between Frequencies

	1920/912 MHz (dB)	5990/1920 MHz (dB)
Theoretical	6.5	9.9
Measured Residential	7.4	12.7
Measured High Rise	10.0	22.3

4.2 Penetration Loss Calculations

The difference in signal level between the received (corrected) signal level inside the building and the reference signal level (at ground level) is defined as the building penetration loss. The building penetration loss is calculated as

$$P_{ref} - P_{rm/cnr} , \tag{7}$$

where P_{ref} is the median reference signal strength, in dBm, and
$P_{rm/cnr}$ is the median of the signal strength in a particular room or corner of a building, in dBm.

We calculated building penetration losses for each building, at each frequency, and for each transmission path separately. The total mean (see Glossary of Terms) building penetration loss was found by calculating the mean of all residential or high rise medians. Standard deviations, σ, were calculated using the formula

$$\sigma = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}} , \tag{8}$$